High Energy Stellar, Protostellar and Protoplanetary Physics: The Science Case and Performance Constraints for Constellation-X

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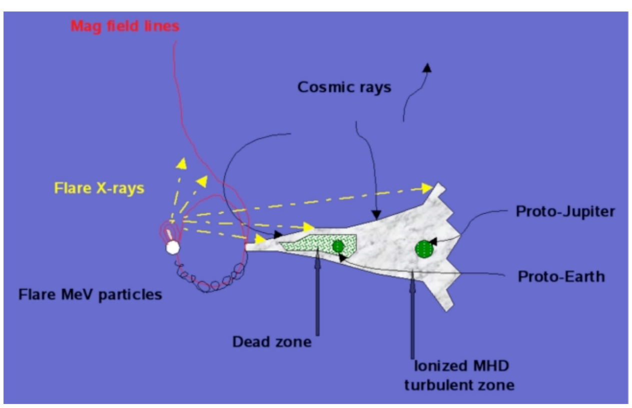
Star and planet formation, the evolution of planetary atmospheres, magnetic dynamo processes at work in stellar interiors, the angular momentum evolution of stars, and the origin and acceleration of stellar winds and mass loss are all manifest in, or dependent on, the processes at work in the X-ray emitting outer atmospheres of stars. High energy phenomena in non-degenerate stars and protostars also offer prototypical examples of plasma and processes that occur on much larger scales in the more distant cosmic X-ray sources---from magnetic reconnection and flares illuminating accretion disks of black holes to the radiatively-driven winds and outflows of these accretion disks, to the hot and tenuous optically-thin plasma of galactic interstellar media and clusters of galaxies. Our current ideas and understanding of these aspects of X-ray astronomy stand on the shoulders of our knowledge of stars, and are advanced by our increasing understanding of the basic plasma properties and processes that we can study in the unusually well-understood environment of stars. Paradoxically, stars also present us with one of the greatest unsolved problems of modern astrophysics: that of the heating mechanism of stellar coronae.

This article addresses both the more important high energy stellar physics science goals for *Constellation-X* and defines specifications and requirements for its instruments, listed in Table 1.



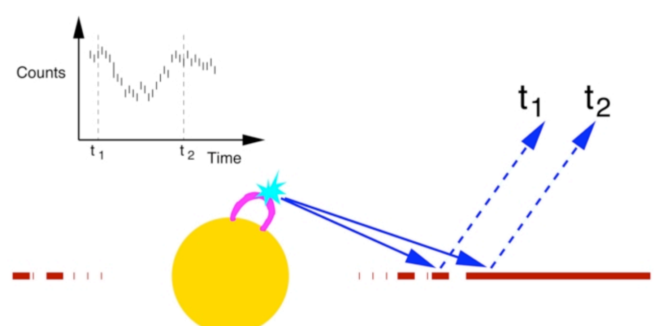


Figure 1 *Left*: A schematic illustrating the influence of stellar activity on protoplanetary disks through magnetically driven high-energy photon and particle emission. Ionizing X-rays penetrates deeply into disks, inducing MHD turbulence, which affects accretion, Jovian planet formation and migration. Terrestrial planets are believed to be formed in a disk “dead zone”, which is sufficiently obscured by overlying material that ionizing X-ray photons and energetic particles cannot penetrate (From Feigelson 2003). *Right*: An illustration of the technique of

reverberation mapping of protoplanetary disks. Bright flares on the central star are reprocessed by the disk and this signal is revealed in spectra in the light of the cold Fe K fluorescence line. The variations of the flux from this line with time can reveal the location of gaps in the disk where planets are forming.

Recent research points to protostellar and pre-main sequence X-ray and energetic particle activity as crucial elements of the processes of star and planet formation (illustrated schematically in Figure 1.) X-radiation from the central object penetrates deeply into the surrounding disks and envelopes, inducing viscosity and MHD turbulence. These affect accretion throughout protostar evolution, and control Jovian planet formation and migration through the competition between gravitational opening and viscous closing of disk gaps (Glassgold et al, 2004). Energetic stellar flares may explain the mystery of the flash melting of meteoritic chondrules and high abundances of short-lived radionuclides in meteoritic calcium-aluminum-rich inclusions through MeV particle spallation (Shu et al, 1997; Feigelson et al, 2002). Young stellar objects (YSOs) are difficult to study at UV-optical wavelengths because they are generally obscured by their parent molecular clouds, but *Constellation-X* will probe through these clouds at X-ray wavelengths.

X-rays from large flares reprocessed into cold Fe K lines by circumstellar disks have been detected in the Ophiuchi Class 1 protostar YLW 16A and several Orion objects (Imanishi et al, 2001; Tsujimoto et al, 2004). The *Constellation-X* XMS would be expected to obtain 1000 counts in this line following a large flare. The time-dependence of the Fe K flux can be used for "reverberation mapping" of the structure of gas and dust in inner protoplanetary disks and gaps that can reveal the locations of inner planets in the process of formation (see Figure 1).

Chandra and *XMM-Newton* grating spectra have detected shock-heated plasma from magnetospheric accretion from two out of the five or so CTTS studied at high resolution to date: in TW Hya (Kastner et al, 2002; Stelzer & Schmitt 2004) and BP Tau (Schmitt et al. 2005). The soft X-ray accretion signatures are high densities seen in the lines of He-like O and Ne and are completely missed at low resolution. Only a small handful of the very nearest CTTS are accessible to *Chandra* and *XMM-Newton* gratings. *Constellation-X* will instead probe accretion signatures at high resolution in stars up to 500 pc away, including those in the nearest regions of copious star formation such as Orion.

About 66% of embedded young clusters are thought to harbor massive stars in their cores. While *Chandra* and *XMM-Newton* are limited to studying more massive YSOs in only a few of the nearest active star forming regions, *Constellation-X* studies will reveal detailed spectra of young massive stars in starburst regions, and will be able to perform a census of the massive stars at the centers of the 80 or so clusters out to a distance of 2kpc. Source confusion is a potential problem and spatial resolution of $\lesssim$ 5" would be required for all but the nearest, more sparse clusters.

The Sun can be imaged in X-rays in fine detail, yet we currently know very little about how other stars can generate huge flares and sustain coronae up to 10,000 times brighter *than that of the Sun, and how these coronae are structured. Constellation-X will provide true Doppler images of stellar coronae through both XMS calorimeter and RGS line profile variations and shifts (illustrated in Figure 2).*

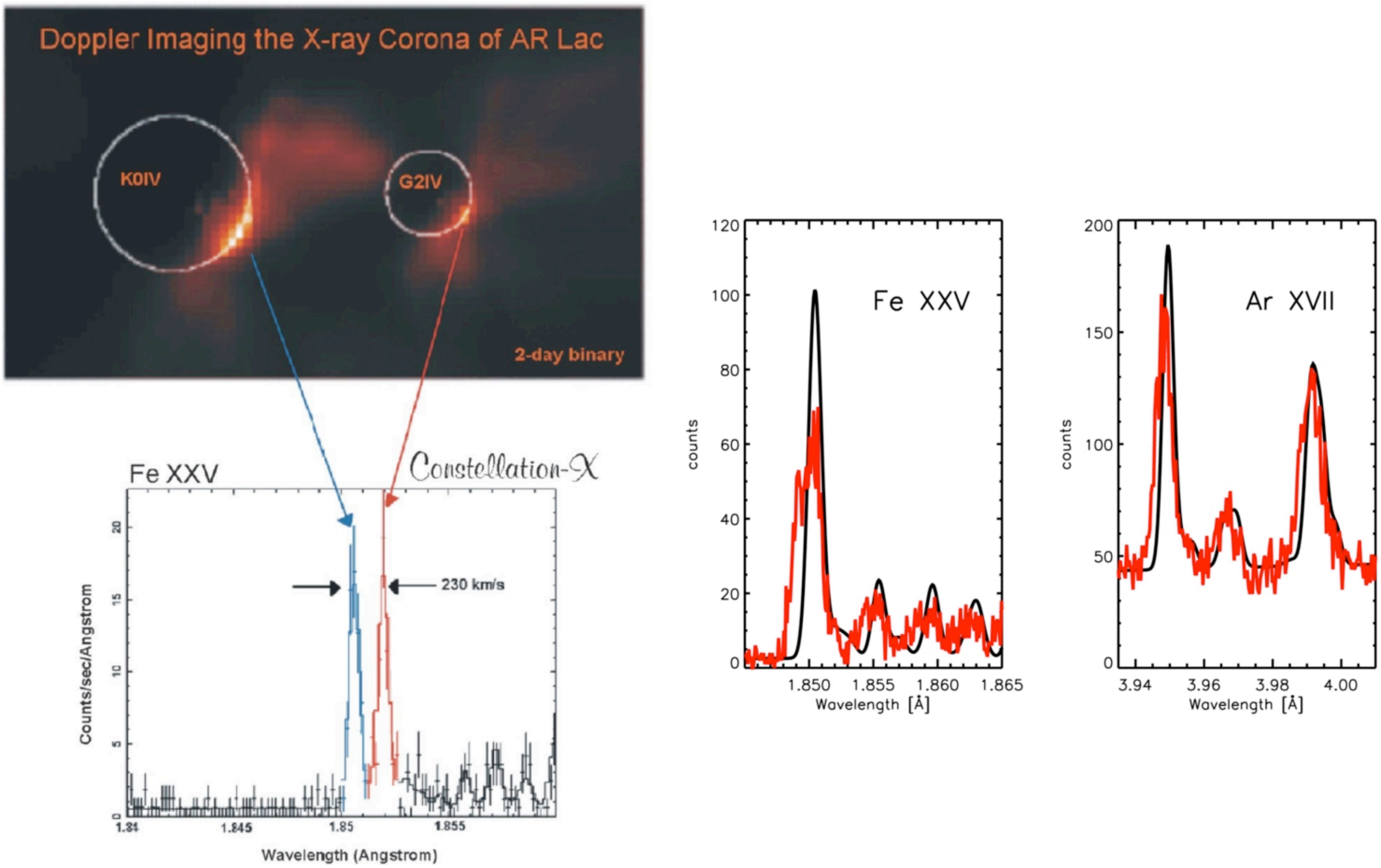


Figure 2 *Left*: The top panel shows an eclipse-mapping spatial deconvolution of the coronae of the RS CVn binary AR Lac as derived from a long EXOSAT exposure. The lower panel shows a simulated 20 ks *Constellation-X* observation of AR Lac, assuming that the exposure was centered on orbital quadrature when the velocity separation of the two stars in this binary system is at its maximum value of 230 km s^{-1}. For simplicity, it is assumed that each star contributes equally to the total X-ray emission. The strong Fe XXV λ 1.85 resonance line is clearly split into two components due to the differential Doppler shifts of the two stars. (Figure courtesy of Steve Drake.) *Right*: Simulated XMS spectra in the region of the He-like Fe and Ar complexes for a 25ks observation of AD Leo. The simulations assumed that the plasma was heated by continuous flaring with upflows in the range of 0-200 km $^{s-1}$, resulting in measurably blueshifted and broadened spectral lines as compared to a model spectrum with no blueshift components. Understanding flares occurring under these conditions (much more extreme than in the sun) will help bridge the gap to the conditions around black hole accretion disks.

While some spatial inference is possible from line shifts and broadening seen in *Chandra* spectra of nearby active stars (Brickhouse et al. 2001; Chung et al. 2004; Hussain et al. 2005; Drake et al. 205), true Doppler imaging requires both very high throughput and spectral resolution. A minimum resolving power that would allow study of the most rapidly rotating nearby systems is $\lambda / \Delta\lambda$ 2000 (FWHM). However $\lambda / \Delta\lambda$ 3000 is required to study more than a small handful of objects. Stars such as AB Dor (K0 V, d = 15pc, P_{rot} = 0.5d), will provide up to 10^6 counts in a day-long observation, allowing for quite detailed coronal images. A few hundred counts in the He-like λ 1.85 resonance line of Fe XXV, and substantially more in H-like and He-like lines of S (λ 4.73, 5.04), Si (λ 6.18, 6.65) and Mg (λ 8.42, 9.17), can be acquired in only a few ks, enable imaging of the very high temperature (10^7 K) plasma separately to that at lower temperatures (several 10^6 K). Doppler imaging of classical T-Tauri stars will allow the location of the x-ray emitting region to be determined, which initial indications suggest are in loops up to 10 stellar radii in size and may have footprints connecting the stellar surface to the accretion disk (Favata etal 2005).

Throughout the universe---in stars, accretion disks, interstellar and intergalactic media for example---magnetic fields store energy imparted by mechanical turbulent or convective plasma motions. This energy can be released again through magnetic reconnection events, whereby the plasma is spontaneously heated and accelerated. Our Sun provides dramatic examples of this process through solar flares. Solar flares and CMEs pose a hazard to both manned and unmanned spacecraft, and understanding them is important for predictive and preventative measures aimed at protecting them. However, magnetic reconnection, flares and coronal mass ejections remain quite poorly understood: what we know is based on what has been learned from the Sun, yet even current models of solar flares fail to match some salient aspects of solar flares (Doschek 1990; Feldman 1990). In particular, blushifted emission expected from upflowing evaporation of the chromosphere (see Figure 2) heated by protons and electrons accelerated in the reconnection event is inadequate to explain the flare emission and sometimes appears prematurely at flare onset. The temporal relationship between hard X-rays (due to the accelerated particles) and soft X-rays (due to chromospheric evaporation) is often not satisfied either, in that soft X-rays can commence *before* the hard X-ray burst.

Time series analyses of EUV and X-ray observations of active stars have provided evidence that plasma at temperatures $\gtrsim 4 \times 10^6$ K arises purely from flares, analogous to the idea of "nanoflare" theories of solar coronal heating (Parker 1988; Guedel 1997; Audard et al. 2000; Kashyap et al. 2002. *Constellation-X* will provide a sensitive test of flare heating through both Doppler shifts and photon arrival times. The *Constellation-X* effective area is more than 10 times that of *XMM-Newton* EPIC at energies > 2 *keV* and is therefore sensitive to flares an order of magnitude fainter. A *Constellation-X* XMS effective area of 6000 cm^2 at E 3 - 6.5 keV and resolving power of $E/\Delta E > 1000$ brings within reach Doppler diagnostics in H-like and He-like S (λ4.73, 5.04), Ar (λ 3.95, 3.73) and Fe (λ1.85). A simulation of a 25 ks XMS observation of the nearby flare star AD Leo (dM3e; d = 4.7pc) is illustrated in Figure 2.

Another major *Constellation-X* breakthrough in the study of stellar flares will be the enormous improvement in photometric precision of flare light curves and spectra, allowing direct measurement of coronal loop resonant frequencies themselves. (Mitra-Kraev et al. 2005) have recently detected oscillations with a period of 750s and an exponential damping time of 2000s in the X-ray emission from a large flare observed on the M-dwarf AT Mic by *XMM-Newton* (illustrated in Figure 3). Oscillations in solar loops are seen routinely (Schrijver et al. 2002; Wang et al. 2003; Mariska 2005) and arise from a resonance in the flare loop whereby the loop plasma is successively compressed and rarified. Such oscillations are possibly present in many stellar flares but at such a low pulsed fraction that they are not detected. The observed period and its decay can be used to determine the magnetic loop length and magnetic field. Loop "wobble" velocities on the Sun have reached up to 200 km s^{-1}. *Constellation-X* detections of loop oscillations, both spectroscopically and photometrically, could provide unique measurements of these quantities in a wide range of stars, from accreting T Tauri stars to evolved giants. Resolving powers of 1000 are needed to make firm detections of line-of-sight velocity components of 100 km s^{-1}.

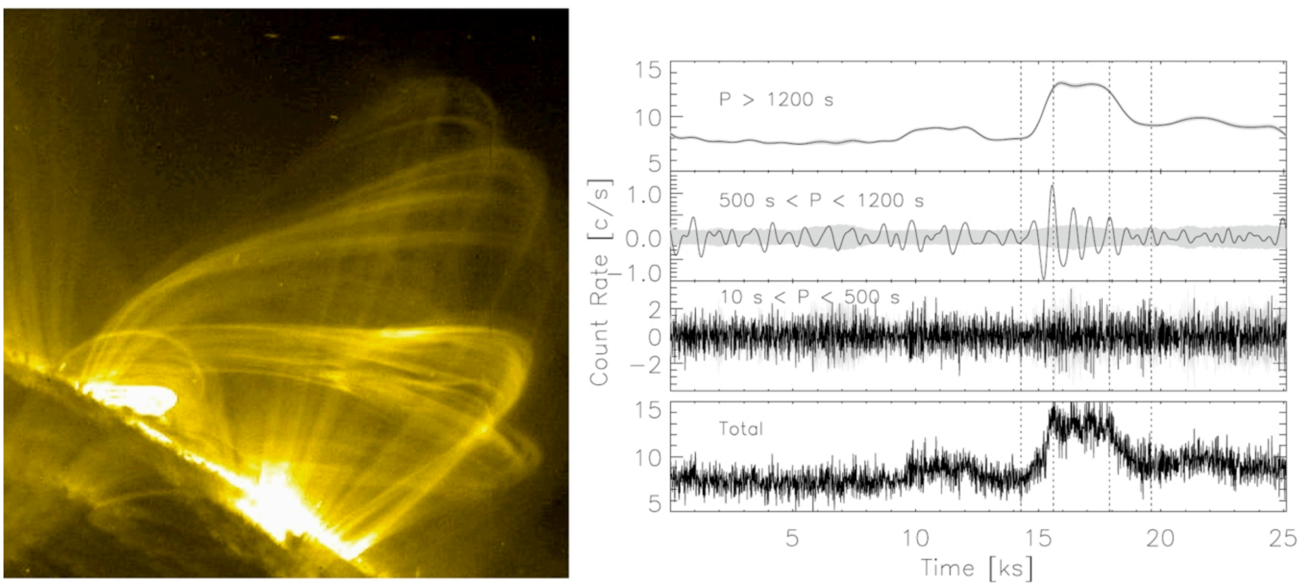


Figure 3 *Left*: Solar coronal loops undergoing transverse oscillations observed by TRACE (Schrijver et al. 2002). Analysis of loop oscillations by (Wang & Solanki 2004) indicates X-ray intensity variations have a pulse fraction as high as 13%. *Right*: An *XMM-Newton* lightcurve of a flare on ATMic decomposed into three frequency bands: low (P > 1200 s) showing gross flare structure; medium (500 s < P < 1200 s) illustrating a coherent flare loop oscillation; and the high frequency (10s <P < 500s) noise component. The sum of these add up to the original data (lower panel). Loop oscillations provide direct diagnostics of magnetic field strength and loop length (Mitra-Kraev et al. 2005).

Detection of hard X-rays in stellar flares would define a major breakthrough for stellar physics. This emission is unequivocally related to impulsively accelerated electrons and ions that do not suffer from magnetic trapping (as radio-emitting electrons do). In the case of the Sun, hard X-rays and gamma rays have been the prime source for the study of energy release physics, particle acceleration in magnetic fields, and coronal heating. The different, and probably more extreme, magnetic configurations in magnetically active stars could lead to quite different acceleration histories and heating efficiencies in large flare events. Detection of hard X-ray components would thus open an entirely new avenue in the study of the energetics of hot, magnetized coronal plasma. For the *Constellation-X* HXT area of a few 10^3 cm^2, bright flares on nearby stars can be detected in only 100s.

The ubiquity of rapidly expanding stellar winds from OB stars are one of the most unexpected and important discoveries of the early NASA space program (e.g. Snow & Morton 1976). Soft X-ray emission is understood in terms of shock instabilities in line-driven winds (Lucy & White 1980); however, the nature of the processes that lead to shocks and X-ray emission are still unclear. One possible geometry for the emission region postulates especially porous and fragmented stellar winds, allowing both blue and redshifted X-rays to penetrate through (e.g. Feldmeier et al. 2003); another suggests that X-rays arise in extended magnetic loops (Underhill 1979) within which both hot upflows and downflows are observed. XMS measurements of the profiles of emission lines such as Ar XVIII (λ3.73), Ca XX (λ3.02) or even Fe XXV (λ1.85) could provide important constraints, as the higher Z lines are likely emitted closer to the stellar surface and thus should become narrower within the fragmented wind scenario. High time resolution X-ray photometry and spectral line profile variations could resolve variations due to different wind fragments or clumps.

Table 1
Instrument Performance Constraints

Performance Aspect	Energy [keV]	Specification Minimum	Goal	Science Drivers
Spectral Resolving Power (λ / Δλ)	0.25-0.6, 6.5	2000	≥ 3000	Flare velocity shifts; Doppler Imaging; Loop resonance
Effective Area	20	1000 cm^2	≥ 3000 cm^2	Non-thermal X-rays from magnetic reconnection flares
	6.5	5000 cm^2	10000 cm^2	Reverberation mapping of protoplanetary disks; Photospheric Fe K fluorescence
	0.25-1.0	2000 cm^2	10000 cm^2	Very low mass stars and brown dwarfs; charge exchange mass loss; Doppler Imaging
Spatial Resolution	0.25-7	5”	< 5”	Star formation regions; stellar clusters; main-sequence mass loss
	> 10	100”	30”	Magnetic reconnection flares
Field of View	0.25-10	2.5’	> 2.5’	Star formation regions; stellar clusters
Timing Resolution	> 0.25	ms	…	Giant magnetic reconnection flares; flare heating
Maximum Count Rate	> 0.25	10^3	10^4	Giant magnetic reconnection flares

Mission Planning Requirements	Roll angle flexibility required for cluster observations, binaries; Efficient mosaicing to observed clusters
Calibration Requirements	Wavelength precision and stability to 10% FWHM PSF/LRF calibration to 10% or better at ≤ 90% power radius
Other Requirements	Minimum Observation ≲ 5 ks for snapshot surveys and larger samples

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